Computational Modeling of the Load Transfer Mechanism in a Heat Exchanger Pile

Tri V Tran*, Dunja Peric**

* Graduate Student, Department of Civil Engineering, 2136 Fiedler Hall, Kansas State University, Manhattan, KS 66502-5000
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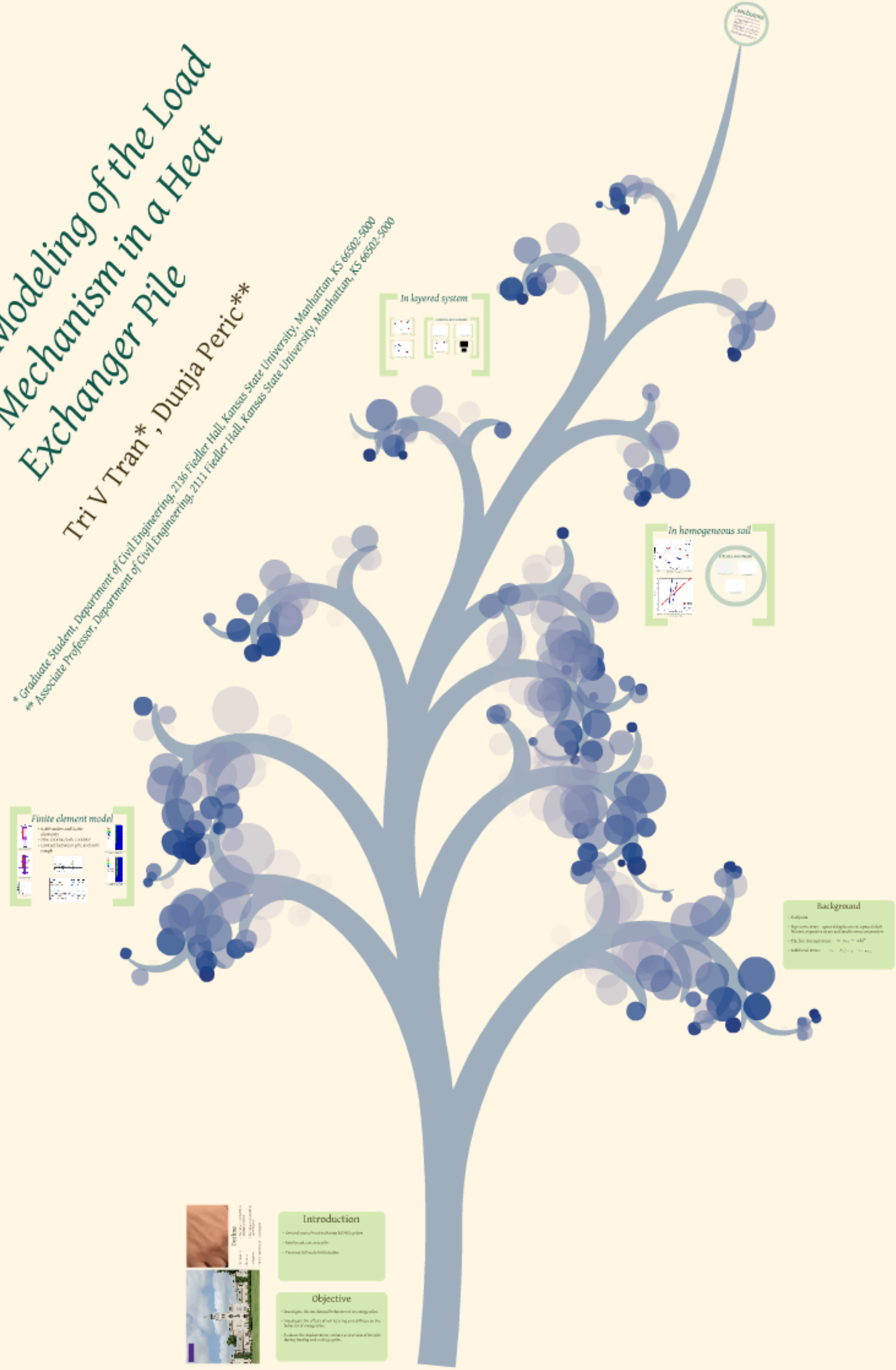

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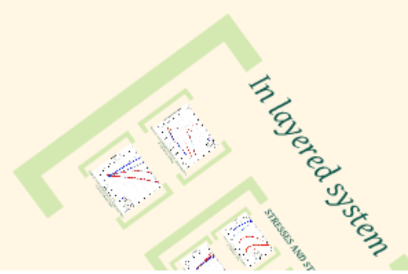

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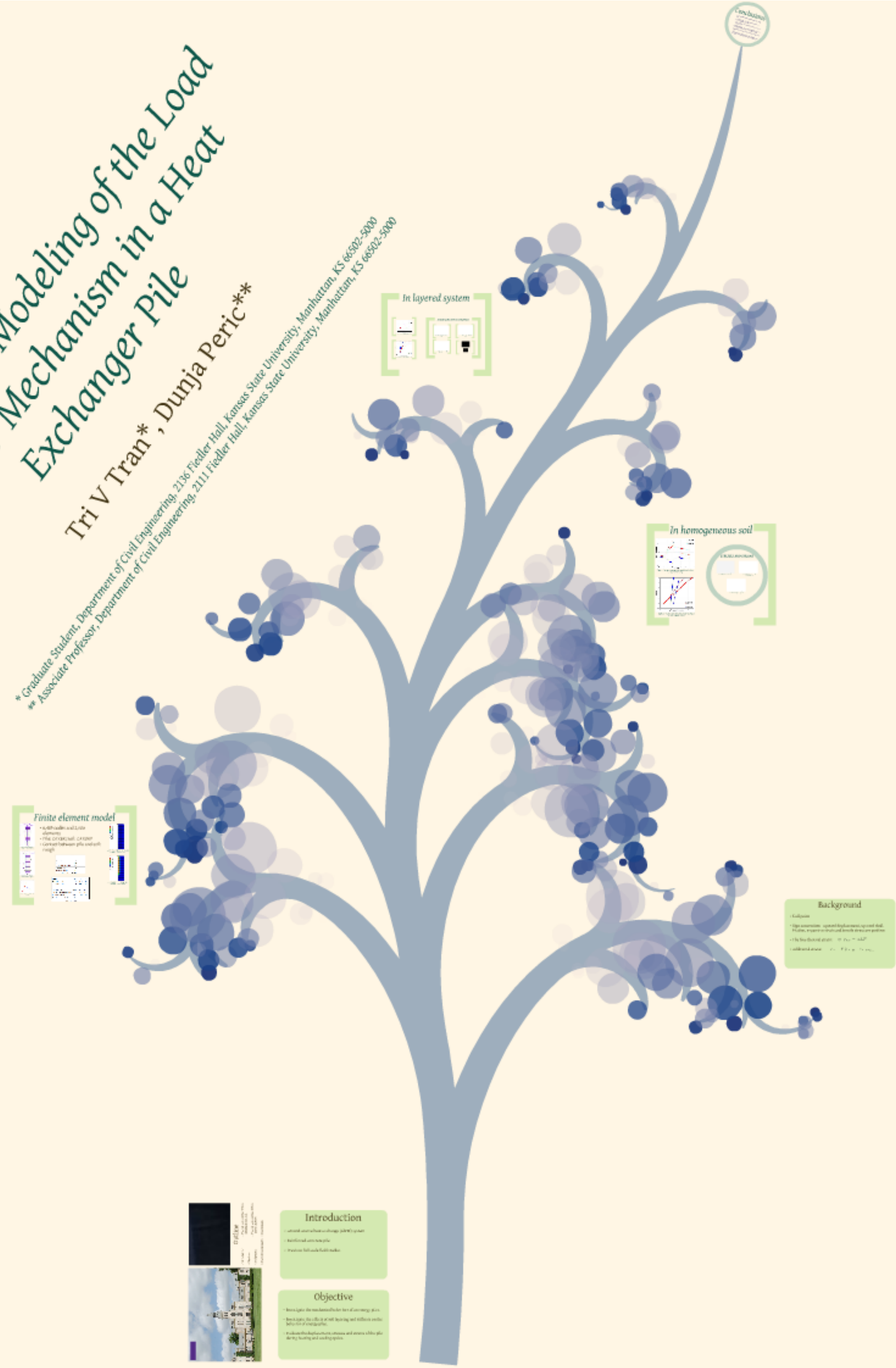

Outline

- Introduction
- Objective
- Background
- Finite element model
- The behavior of the HEP in homogeneous soil
- The behavior of the HEP in layered system
- Conclusions

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Introduction

- Ground source heat exchange (GSHE) system
- Reinforced concrete pile
- Previous full scale field studies

No. of case	Author / Year	Location of the project
1	Laloui et al. (2006) in [1]	Lausanne / Switzerland
2	Brandl (2006) in [2]	Bad Schallerbach / Austria
3	Bourne-Webb et al. (2009) in [3]	Lambet College / London
4	McCartney and Murphy (2012) in [4]	Denver / Colorado
5	Murphy et al. (2014) in [5]	US Air Force Academy
6	Sutman et al. (2014) in [6]	Richmond / Texas

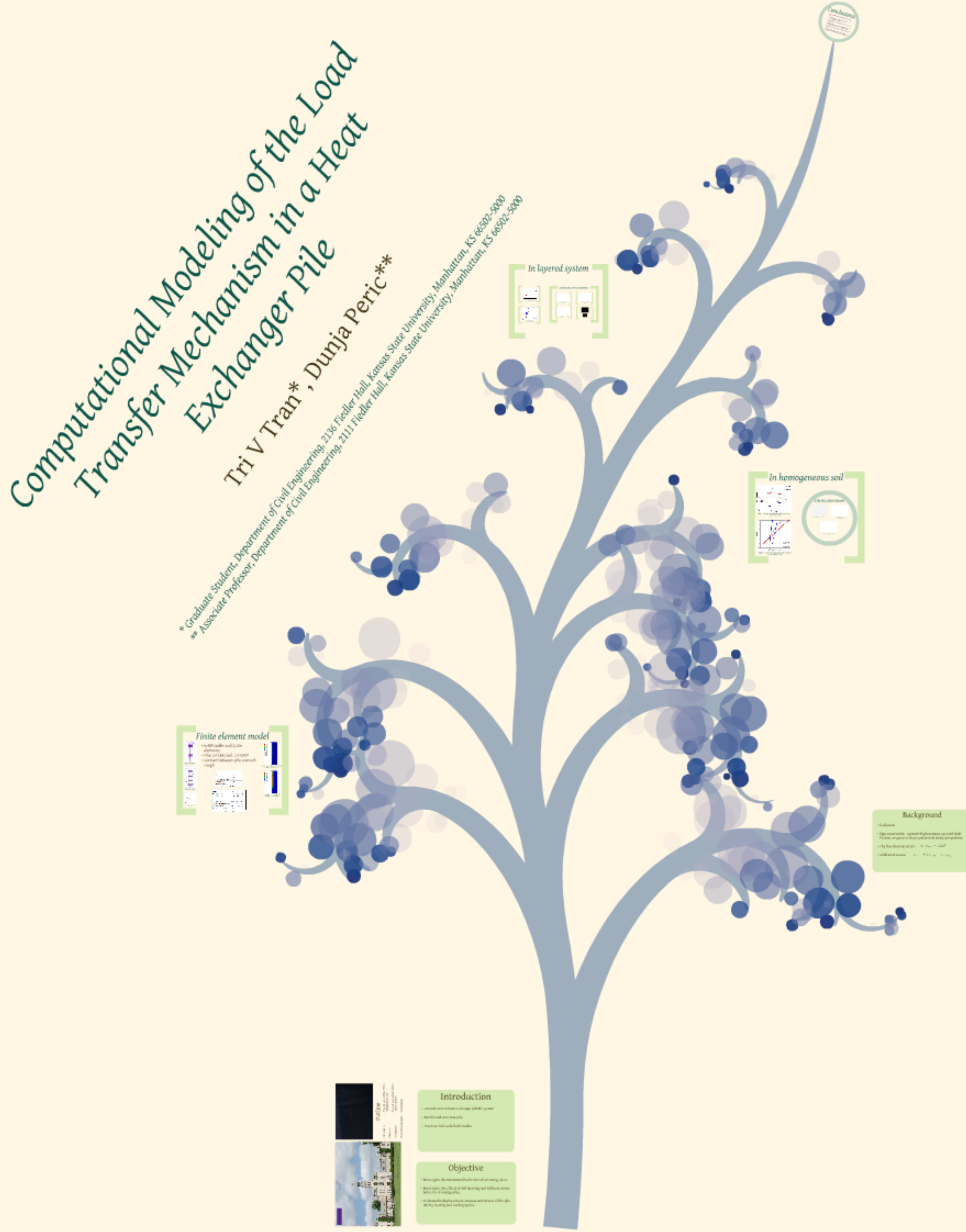
Table 1. Previous studies on full scale field experiments on HEP

Objective

- Investigate the mechanical behaviors of an energy piles.
- Investigate the effects of soil layering and stiffness on the behavior of energy piles.
- Evaluate the displacement, stresses and strains of the pile during heating and cooling cycles.

Background

- Null point
- Sign convention: upward displacement, upward shaft friction, expansive strain and tensile stress are positive
- The free thermal strain: $\epsilon_{T-Free} = \alpha \Delta T$
- Additional stress: $\sigma_T = E\left(\epsilon_{T-O} - \epsilon_{T-Free}\right)$



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In layered system
In homogeneous soil
Finite element model
Background
Introduction
Objective

Finite element model

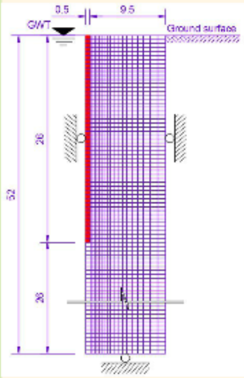

Figure 4. FE model and boundary conditions in a homogeneous soil

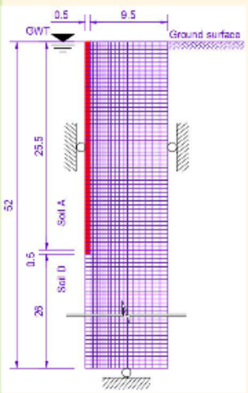

Figure 5. FE model and boundary conditions in a layered system

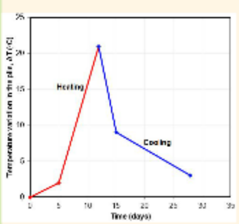

Figure 6. The history of temperature imposed on the pile

- 6,489 nodes and 2,080 elements
- Pile: CAX8R; Soil: CAX8RP
- Contact between pile and soil: rough

Property	Reinforced concrete pile
Young's modulus, E (MPa)	29,200
Poisson's ratio, ν	0.177
Density, ρ (kg/m³)	2,500
Coefficient of thermal expansion, α (°C⁻¹)	1x10⁻⁵
Heat capacity, C (J/m³ °C)	2x10⁶
Thermal conductivity, λ (W/m/°C)	2.1

Table 2. Reinforced concrete pile properties

Property	Soil A	Soil B	Soil D
Bulk modulus, K (MPa)	113.10	983.33	1,860
Shear modulus, G (MPa)	77.87	19.80	1,675
Poisson's ratio, ν	0.177	0.49	0.157
Mass density, ρ (kg/m³)	2,500	2,000	2,550
Coefficient of thermal expansion, α (°C⁻¹)	1x10⁻⁵	1x10⁻⁴	1x10⁻⁶
Heat capacity, C (J/m³ °C)	2.4x10⁶	2.4x10⁶	2.0x10⁶
Thermal conductivity, λ (W/m/°C)	1.8	1.8	1.1

Table 3. Soil properties

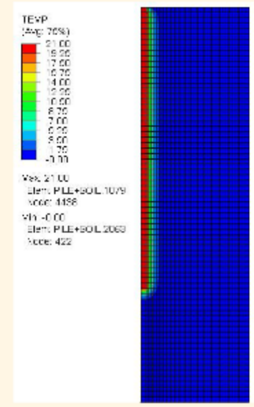

Figure 7. The distribution of temperature at the end of heating phase

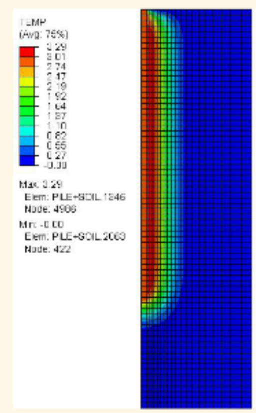

Figure 8. The distribution of temperature at the end of cooling phase

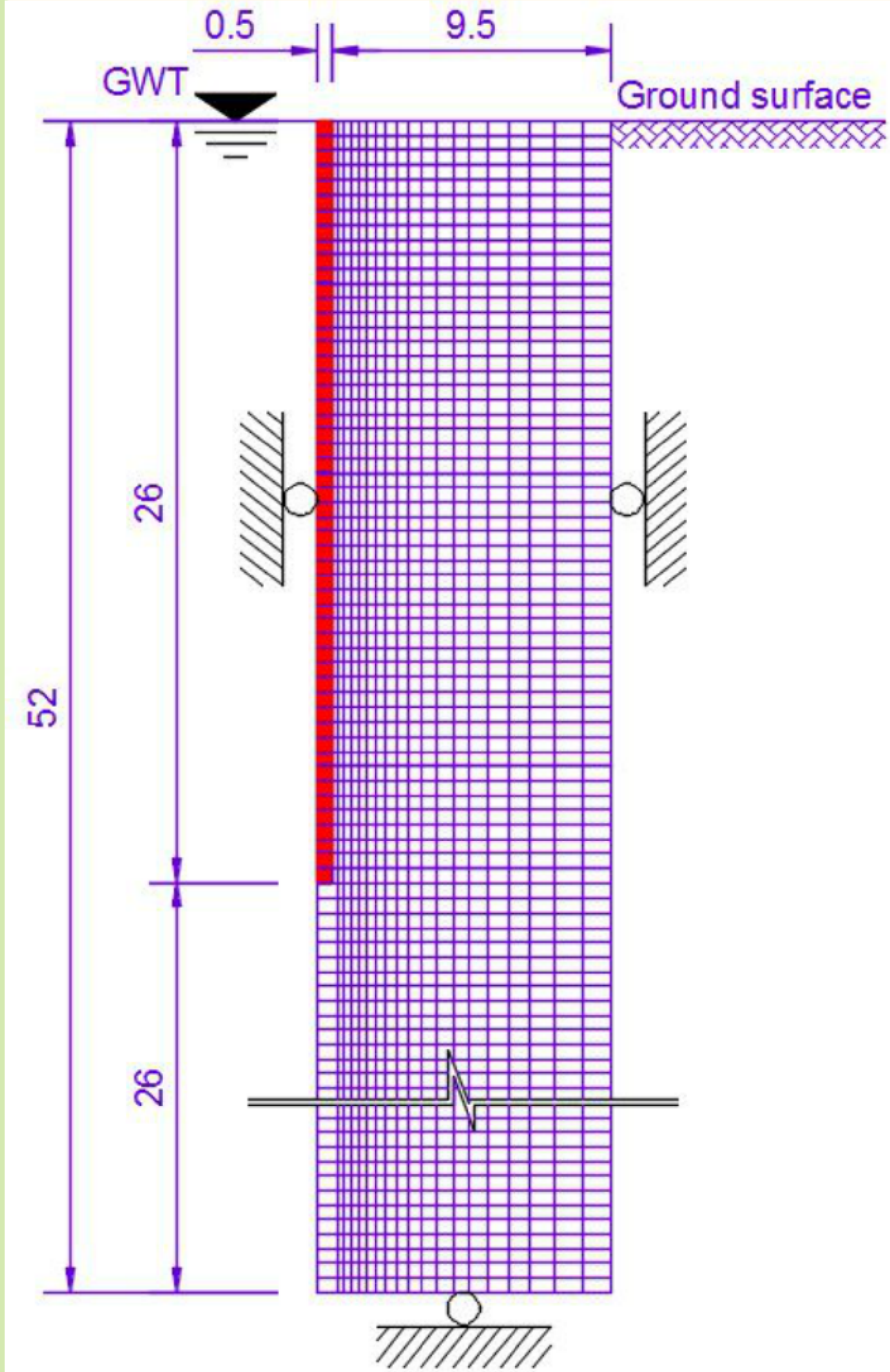

Figure 4. FE model and boundary conditions in a homogeneous soil

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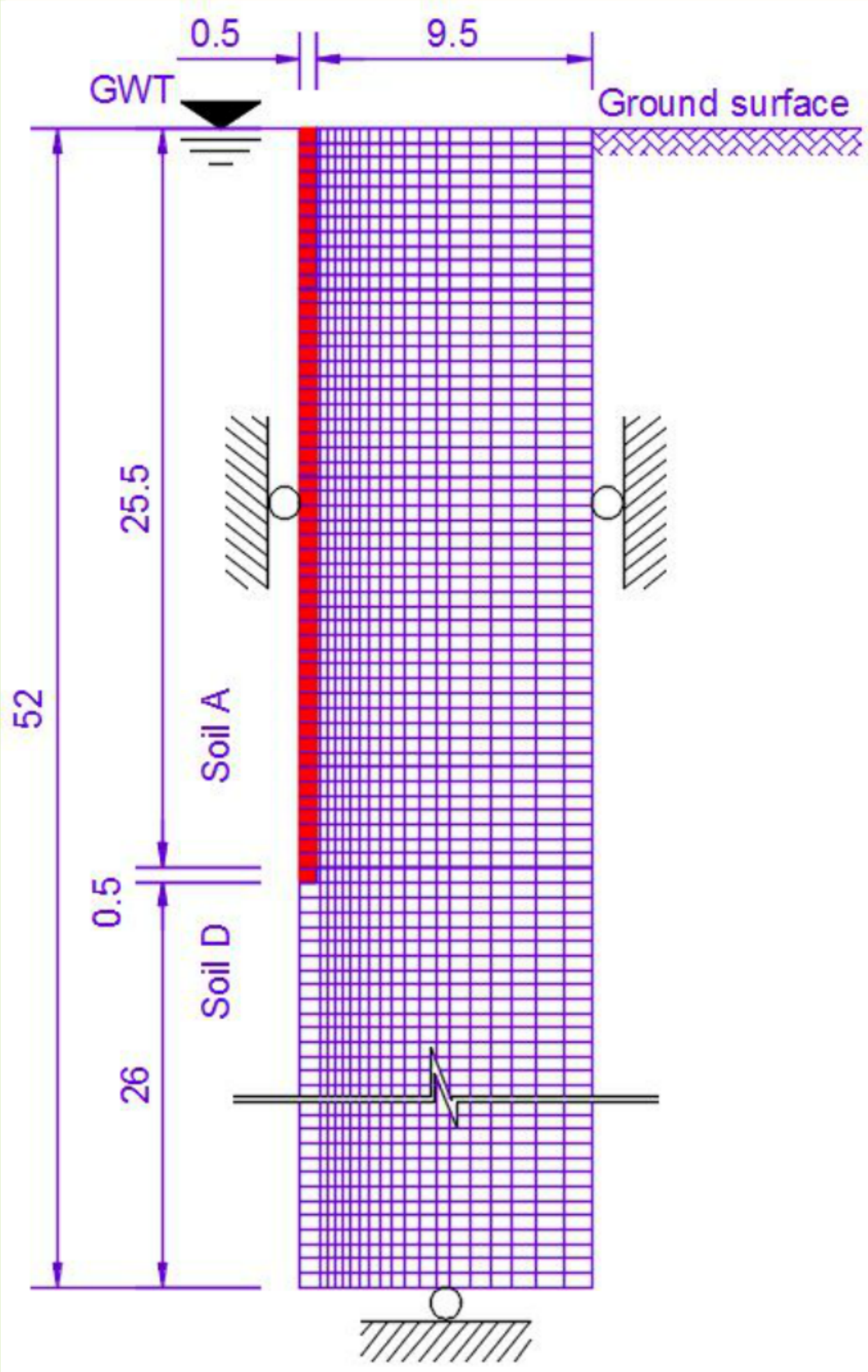


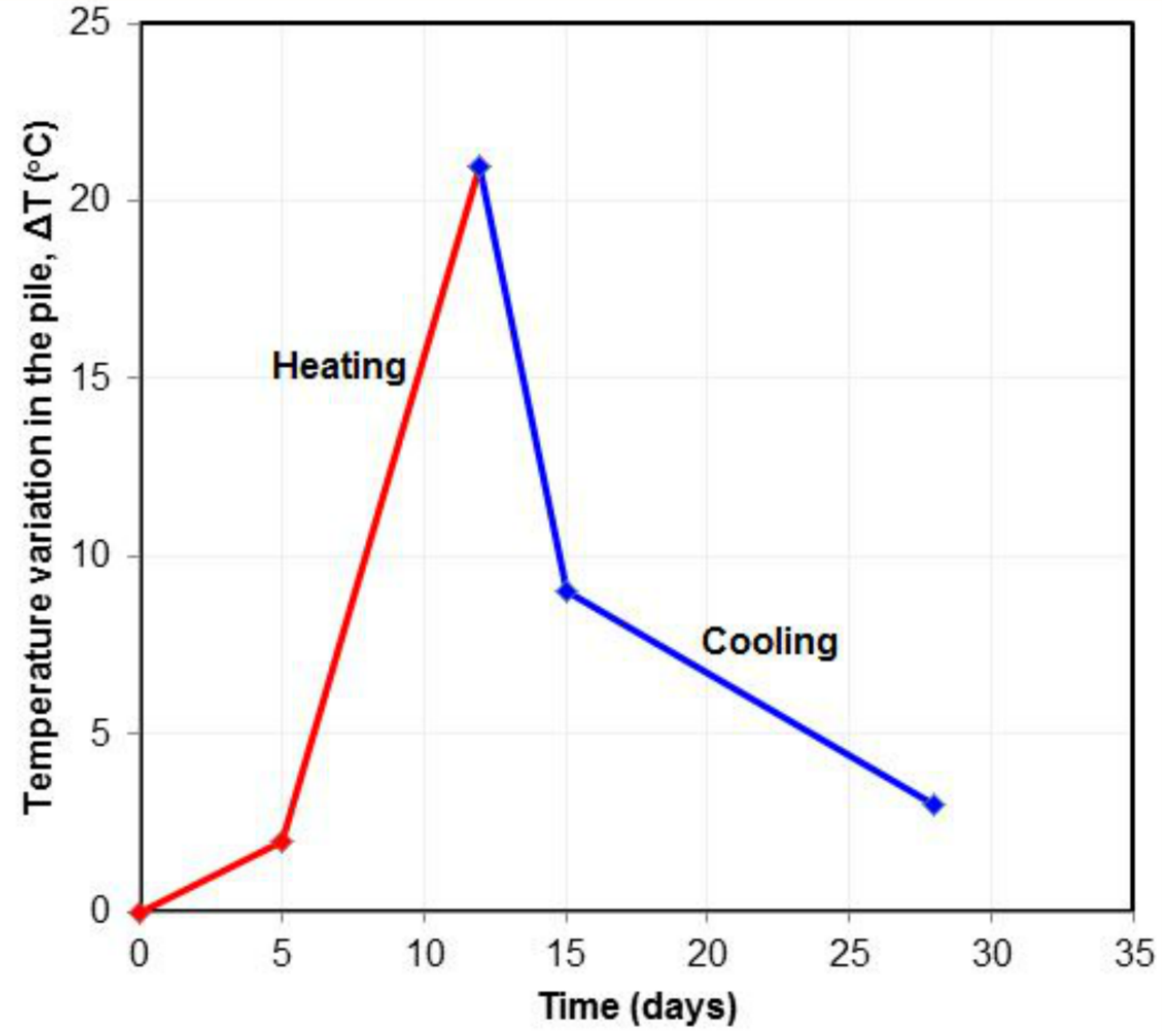
Figure 5. FE model and boundary conditions in a layered system

Property	**Reinforced concrete pile**
Young's modulus, E (MPa)	29,200
Poisson's ratio, ν	0.177
Density, ρ (kg/m^3)	2,500
Coefficient of thermal expansion, α ($^\circ C^{-1}$)	1×10^{-5}
Heat capacity, C ($J/m^3\ ^\circ C$)	2×10^{6}
Thermal conductivity, λ ($W/m/^\circ C$)	2.1

Table 2. Reinforced concrete pile properties

Property	**Soil A**	**Soil B**	**Soil D**
Bulk modulus, K (MPa)	113.10	983.33	1,860
Shear modulus, G (MPa)	77.87	19.80	1,675
Poisson's ratio, ν	0.177	0.49	0.157
Mass density, ρ (kg/m^3)	2,500	2,000	2,550
Coefficient of thermal expansion, α ($^\circ$C^{-1})	$1x10^{-5}$	$1x10^{-4}$	$1x10^{-6}$
Heat capacity, C (J/m^3 $^\circ$C)	$2.4x10^6$	$2.4x10^6$	$2.0x10^6$
Thermal conductivity, λ (W/m/$^\circ$C)	1.8	1.8	1.1

Table 3. Soil properties



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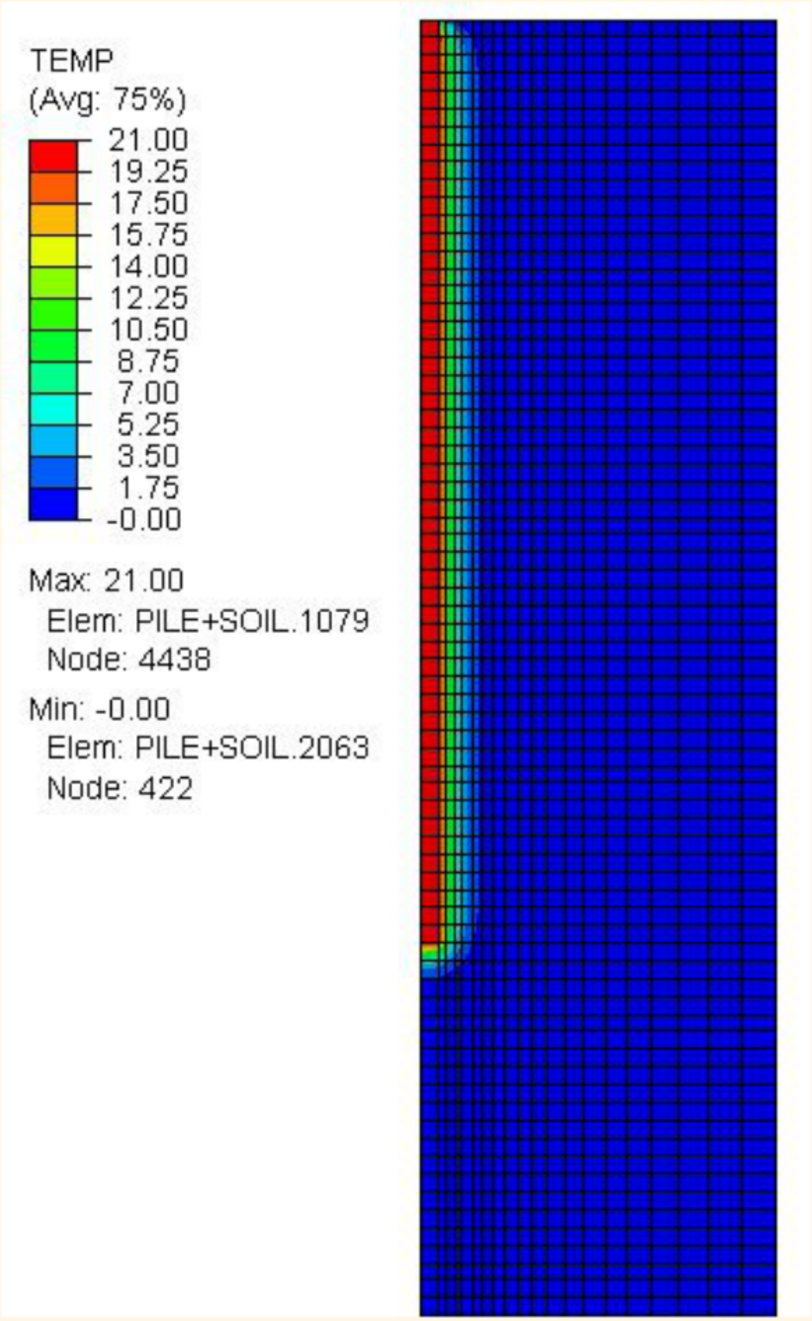

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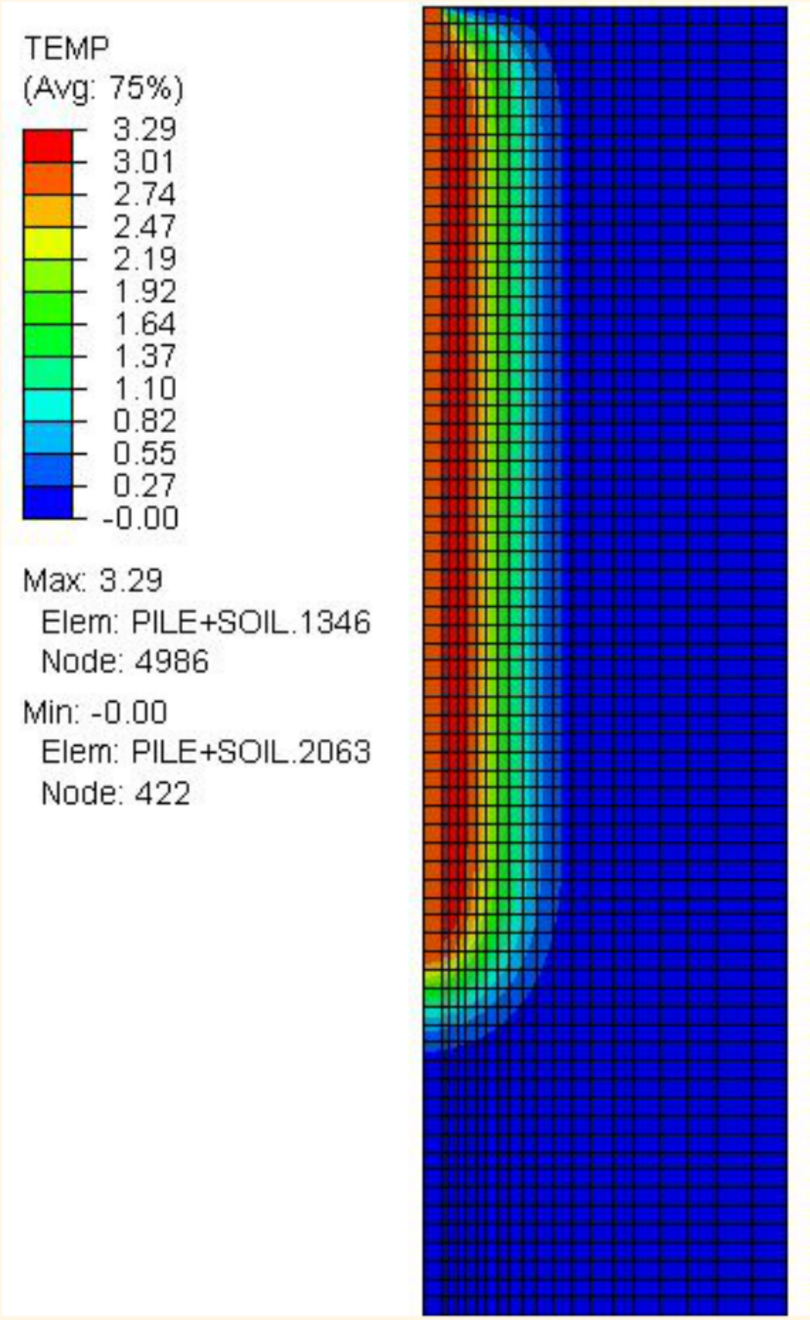


Figure 8. The distribution of temperature at the end of cooling phase

In homogeneous soil

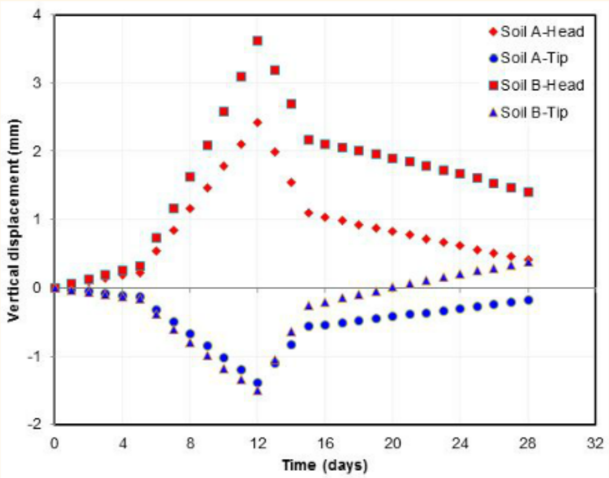


Figure 9. Vertical displacement of the pile head and toe during thermal loading

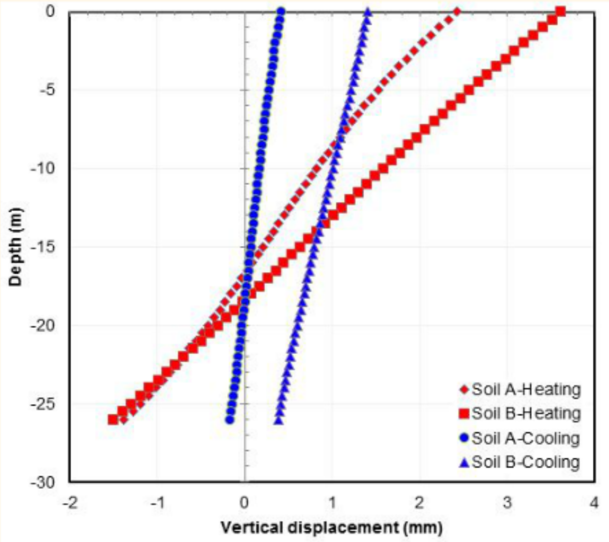


Figure 10. Vertical displacements of the pile with depth at 21 and 3 degree Celsius

STRESSES AND STRAINS

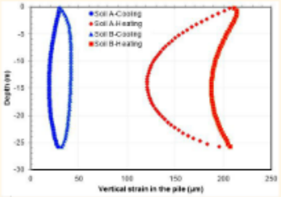


Figure 11. Vertical strains in the pile with depth at 21 and 3 degree Celsius

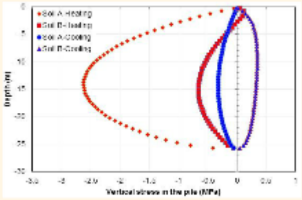


Figure 12. Vertical stress in the pile with depth at 21 and 3 degree Celsius

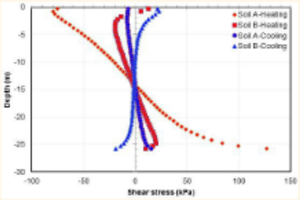
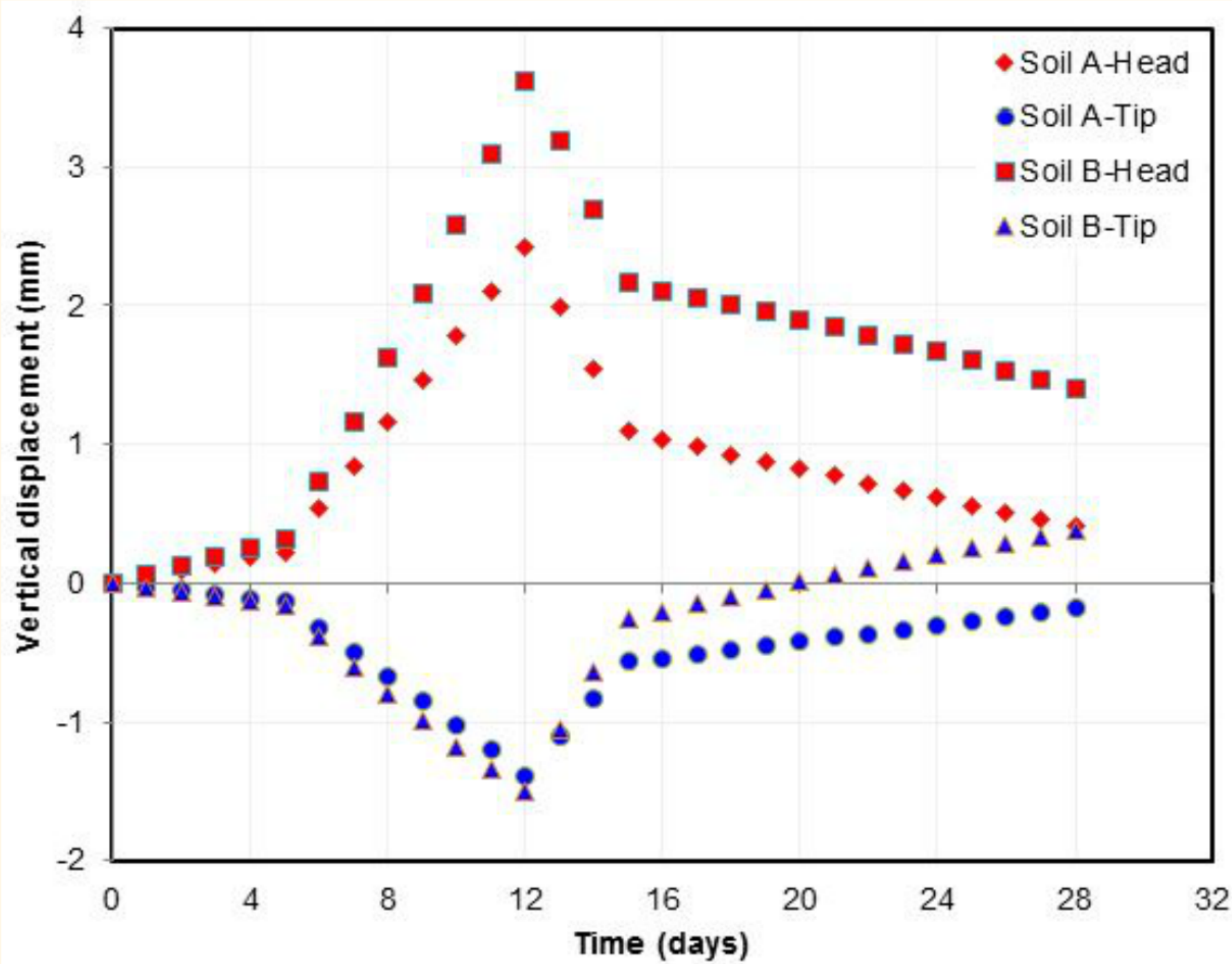


Figure 13. Shear stress next to pile with depth at the end of heating and cooling phases



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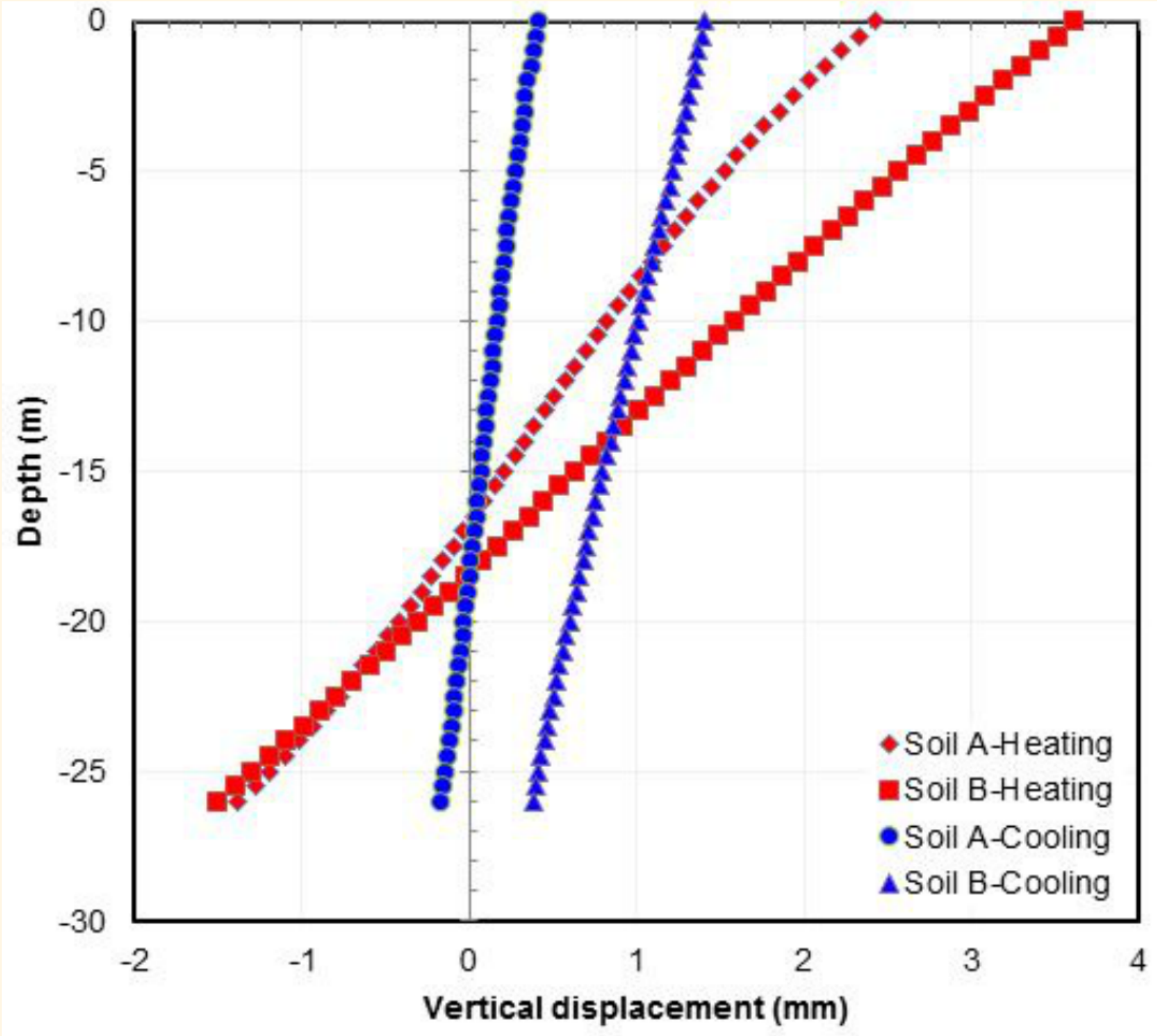

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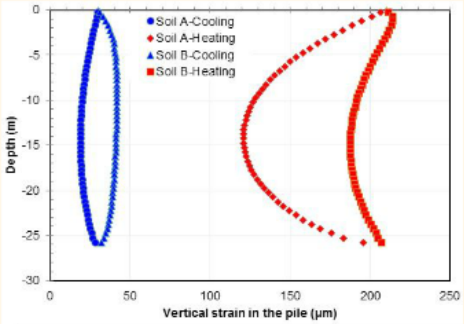

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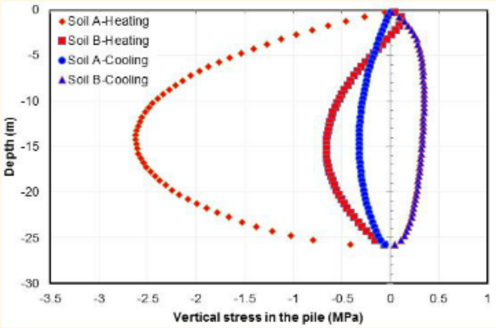

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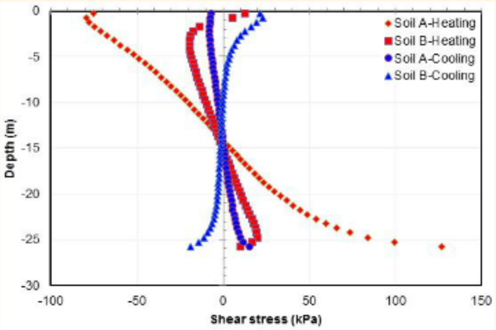

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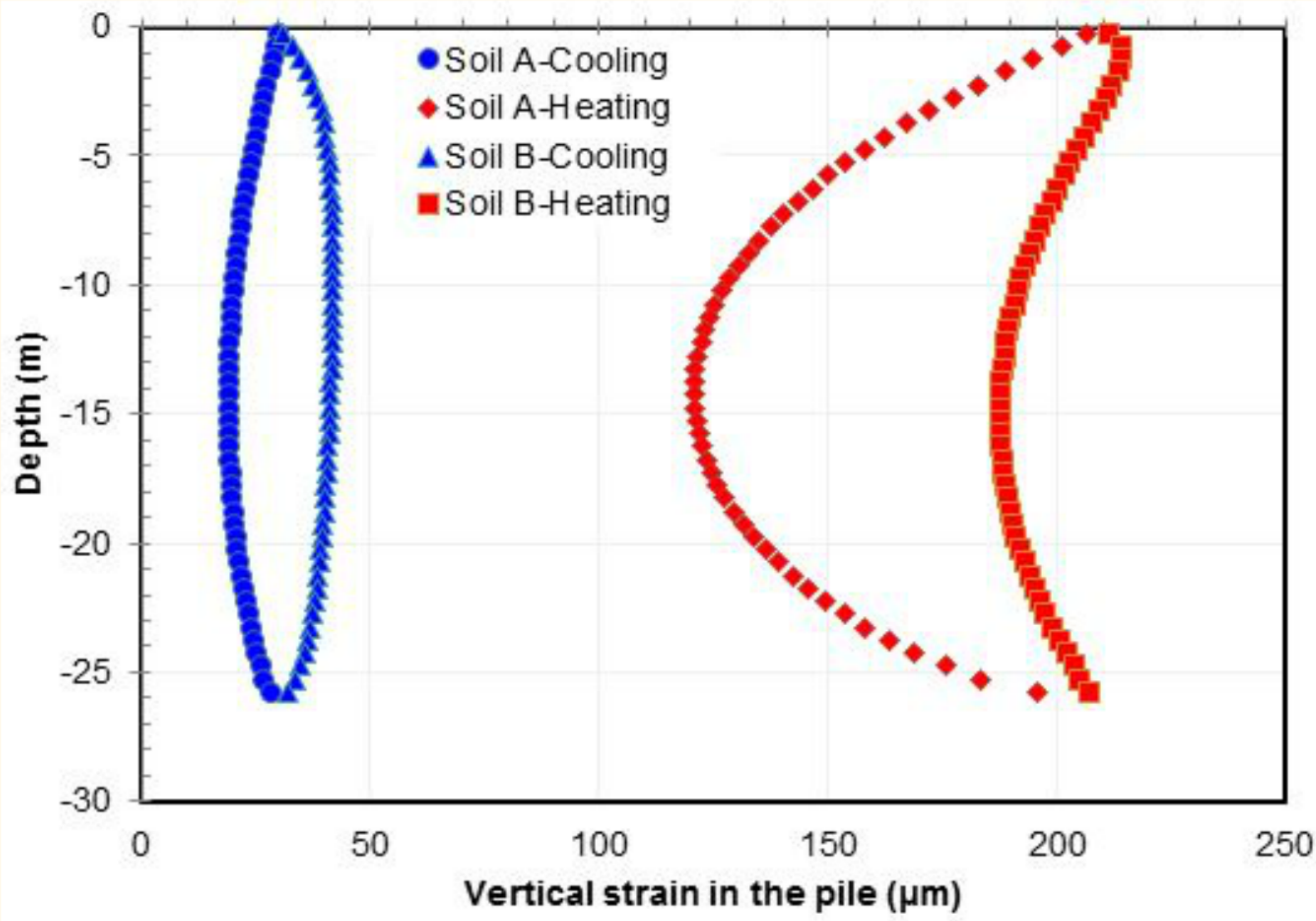

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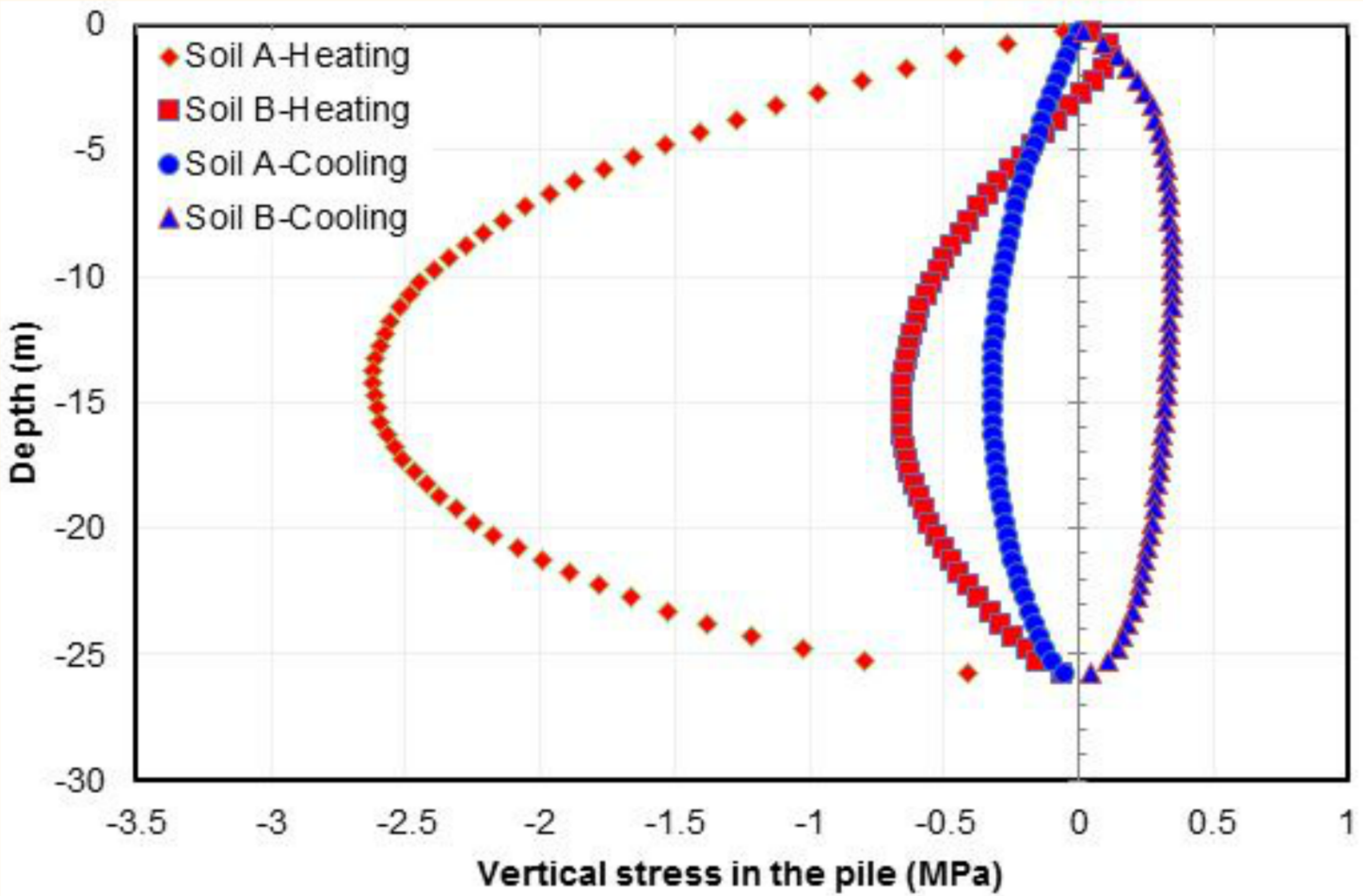

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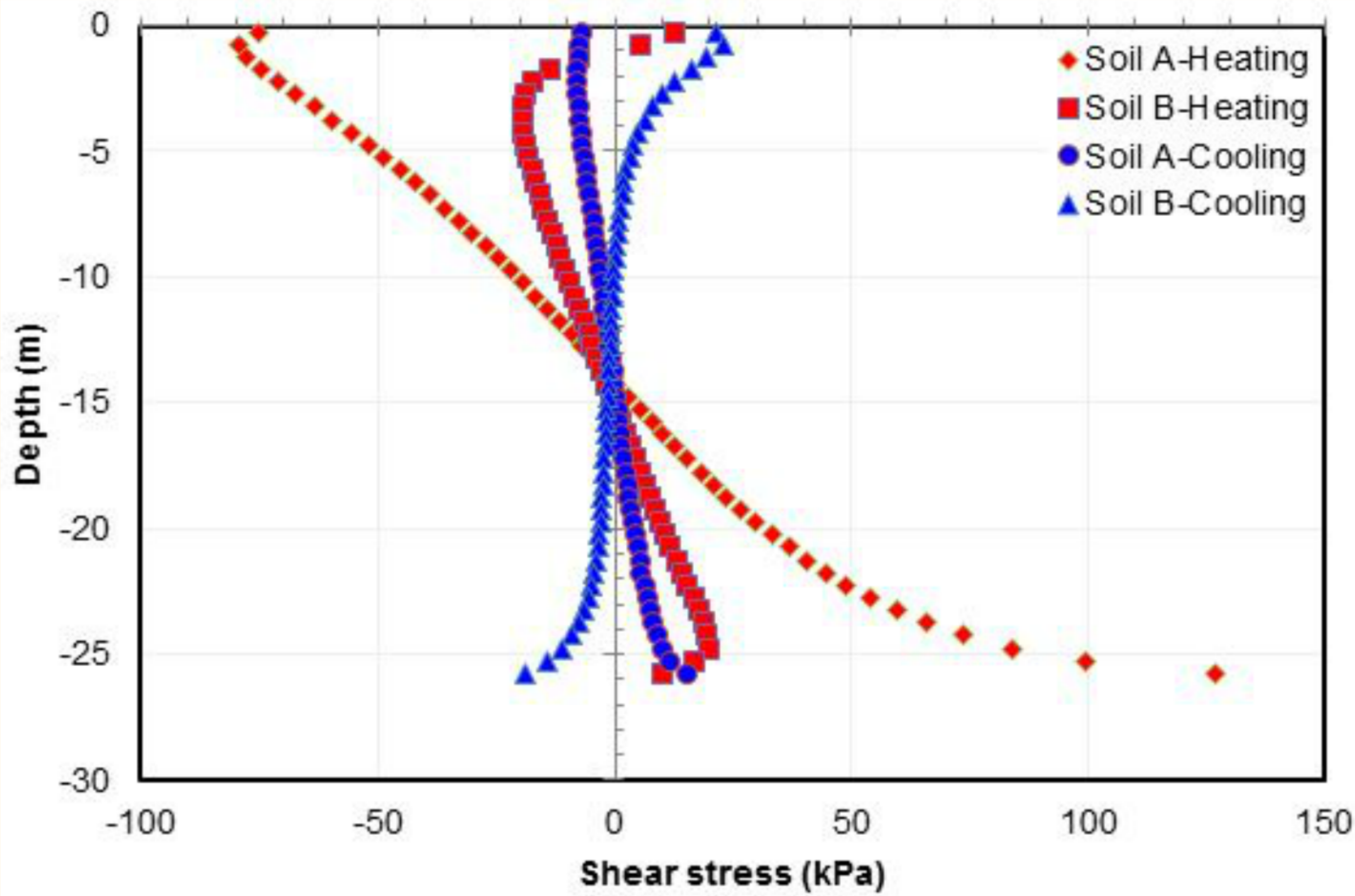

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In layered system

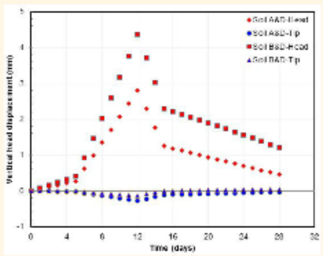


Figure 14. Vertical displacement of the pile head and toe during thermal loading

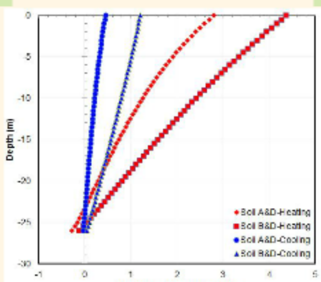
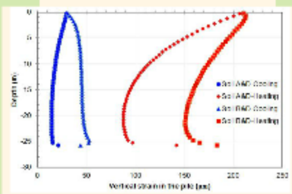


Figure 15. Vertical displacement of the pile with depth at 21 and 3 degree Celsius

STRESSES AND STRAINS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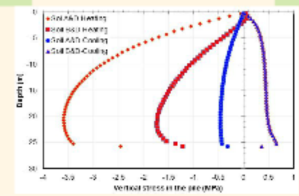


Figure 17. Vertical stress in the pile with depth at 21 and 3 degree Celsius

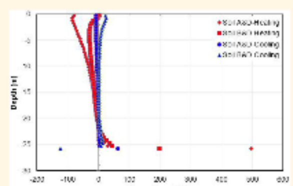
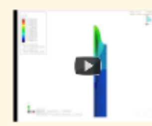
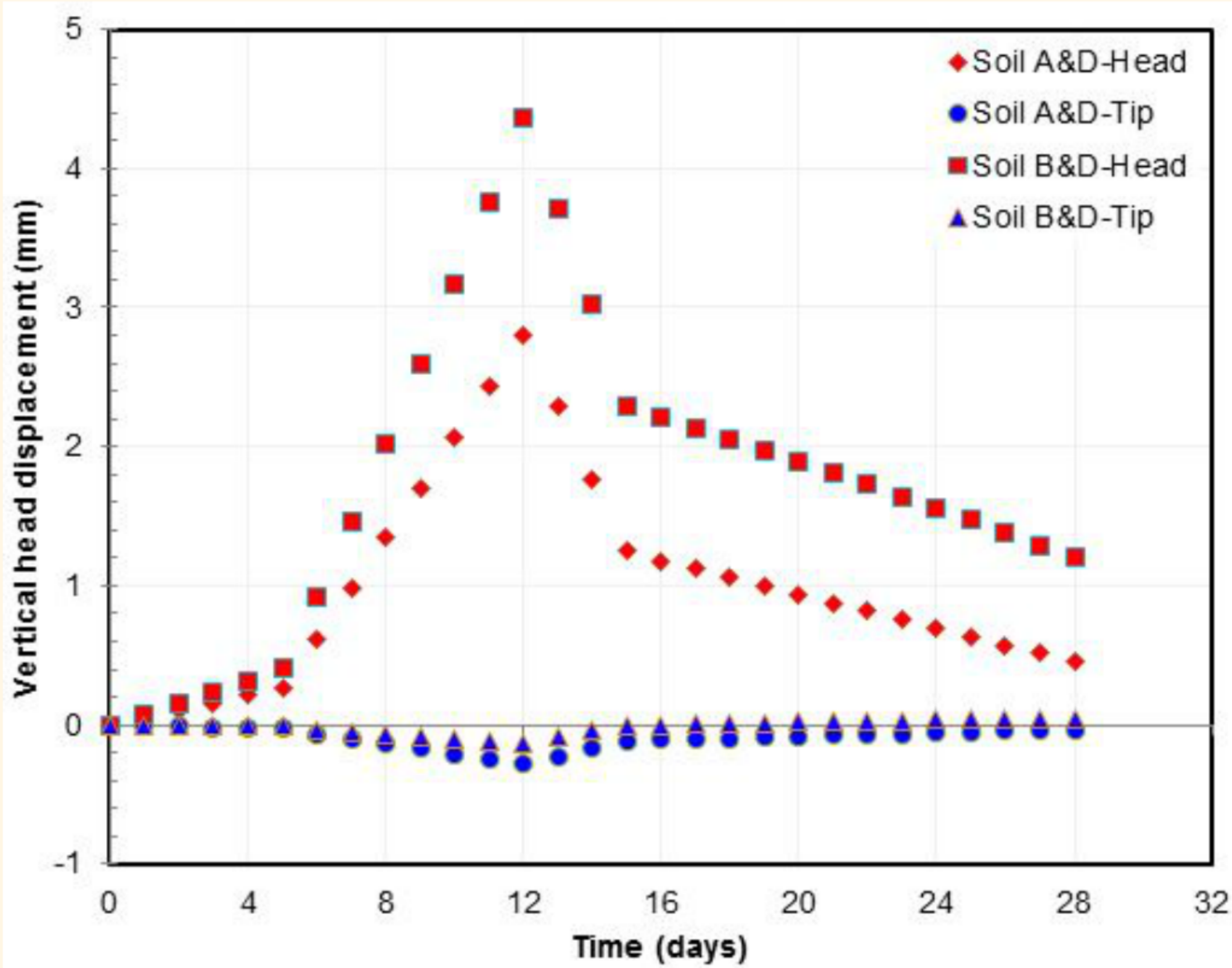


Figure 18. Shear stress next to pile with depth at the end of heating and cooling phases





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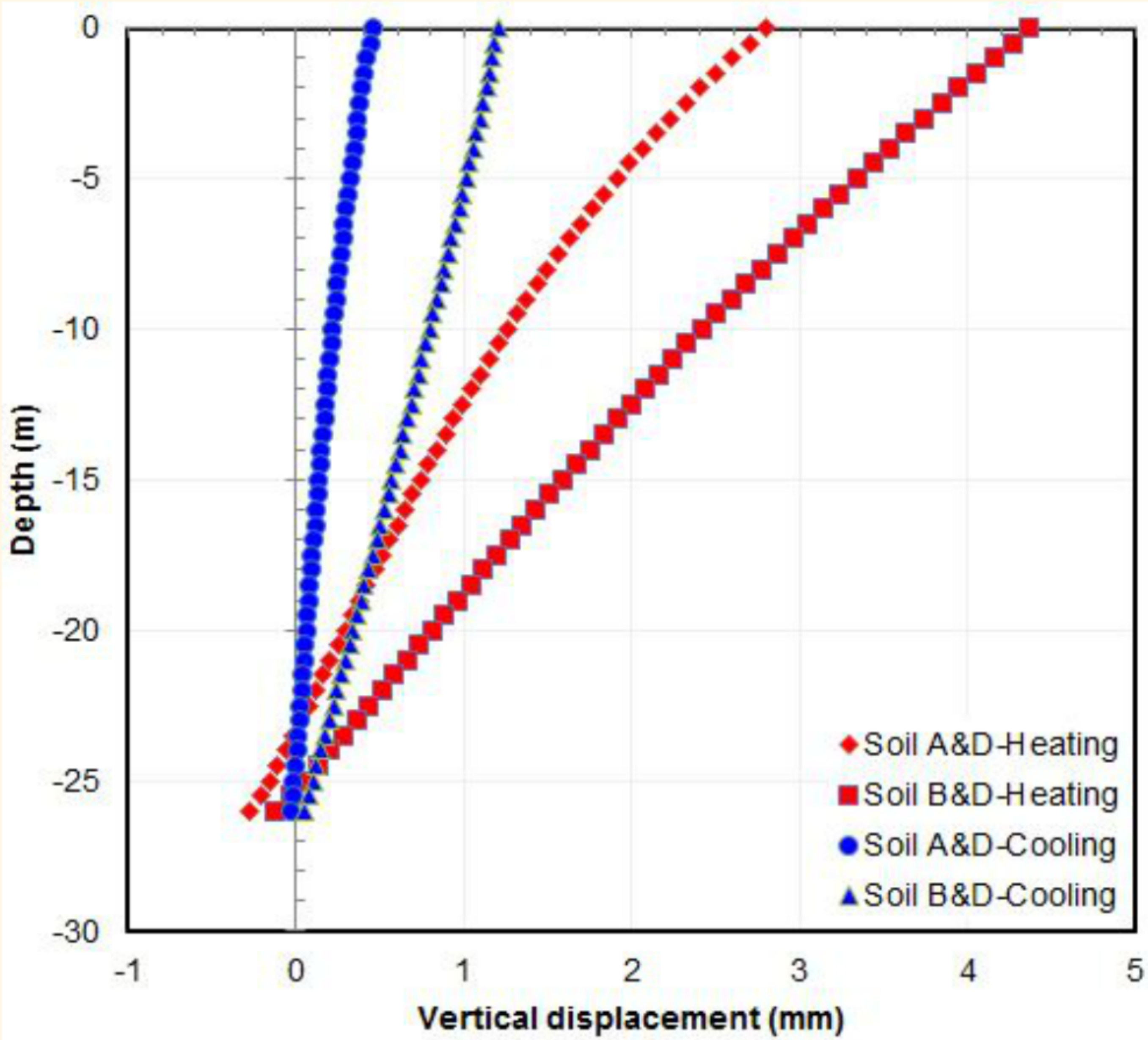

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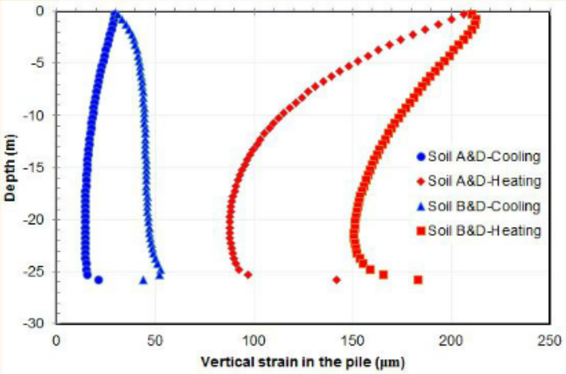

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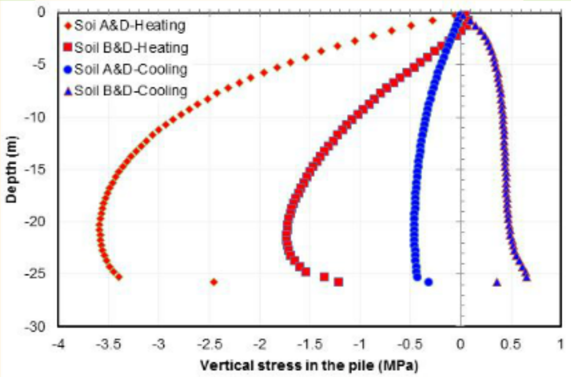

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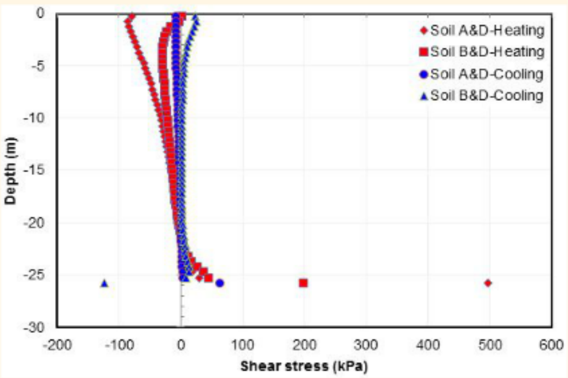

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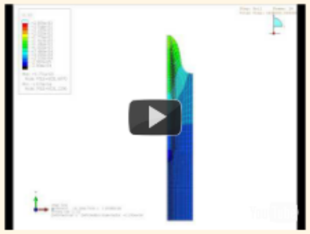

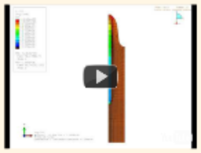

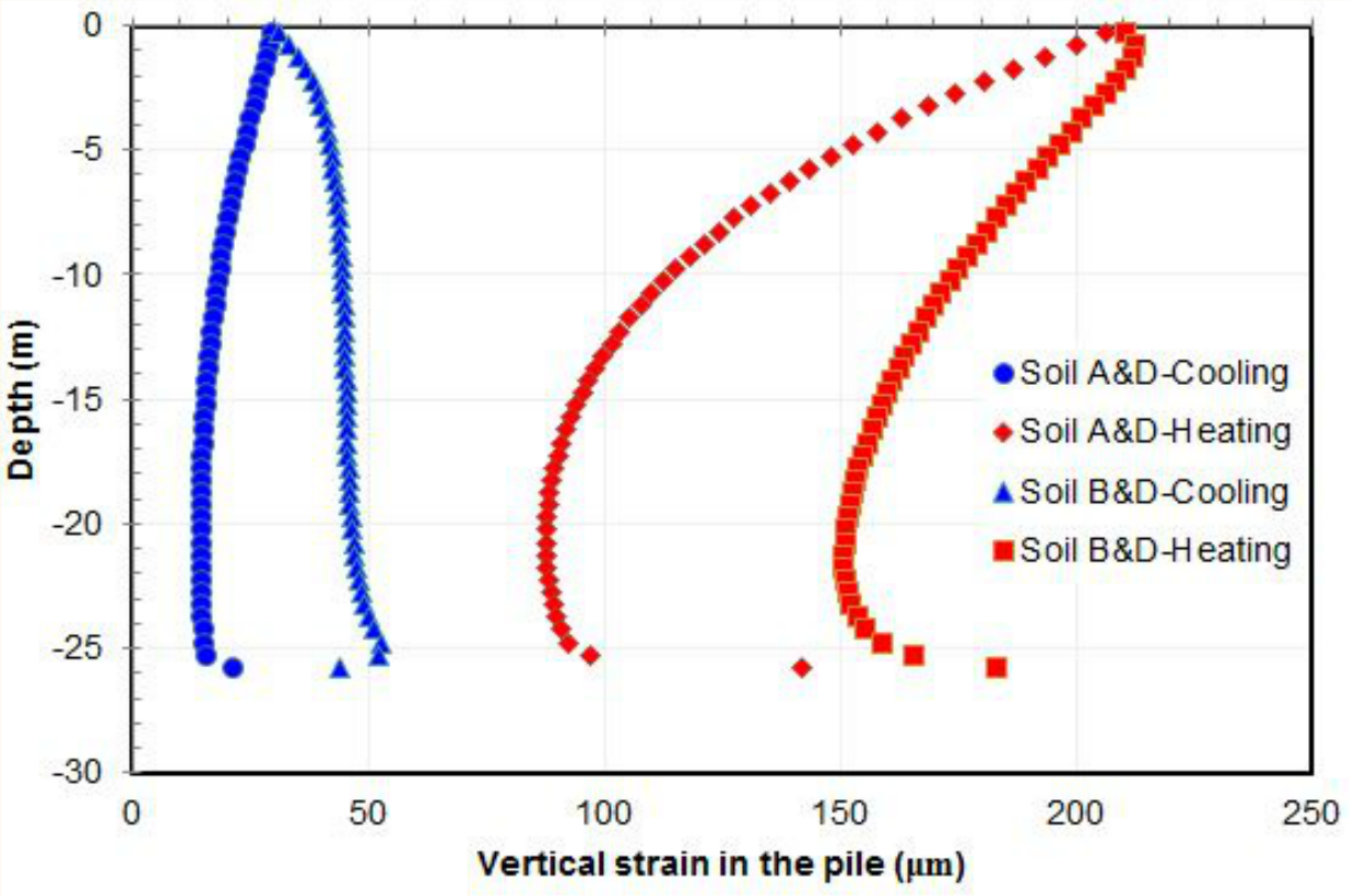

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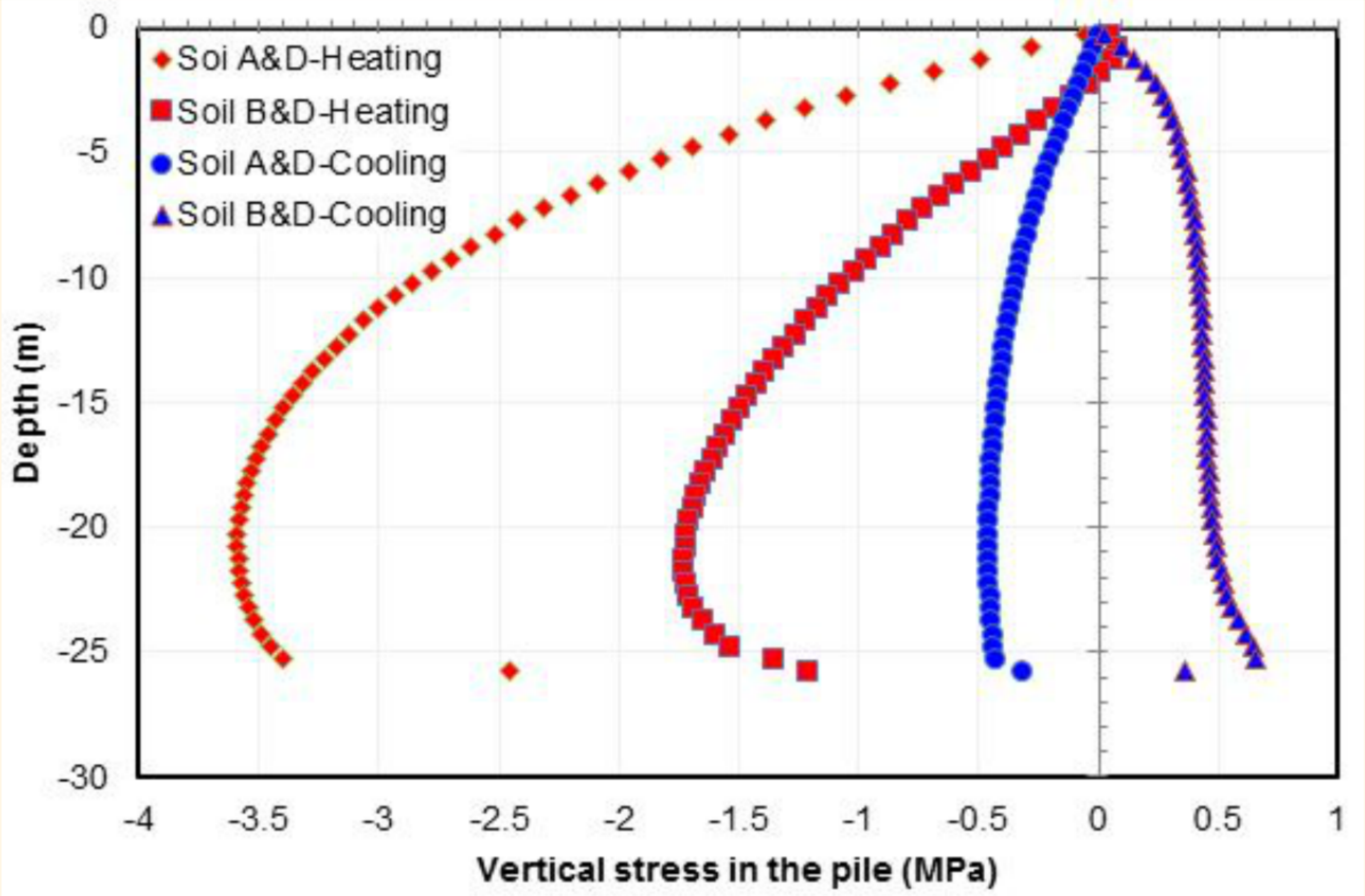

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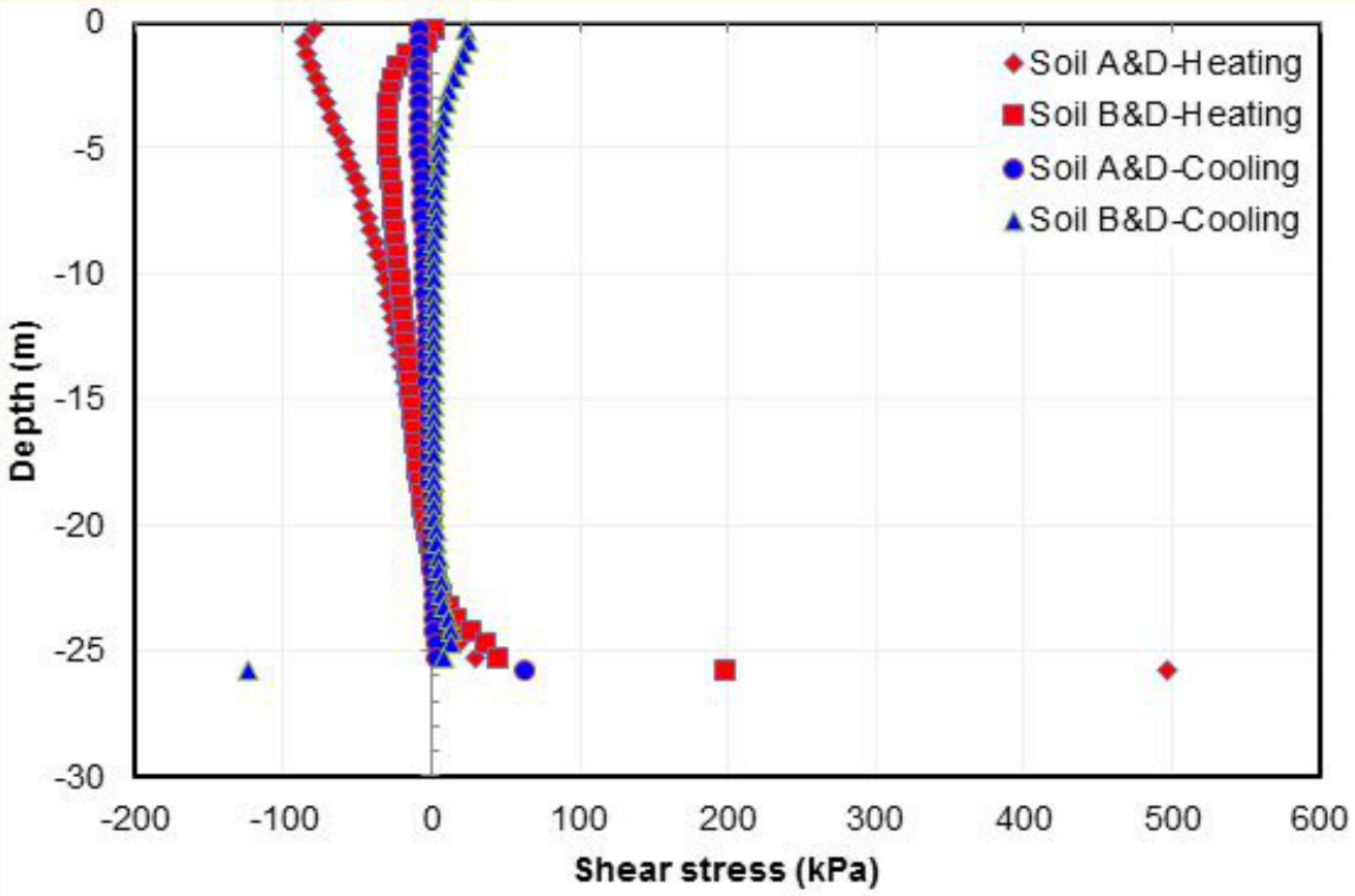

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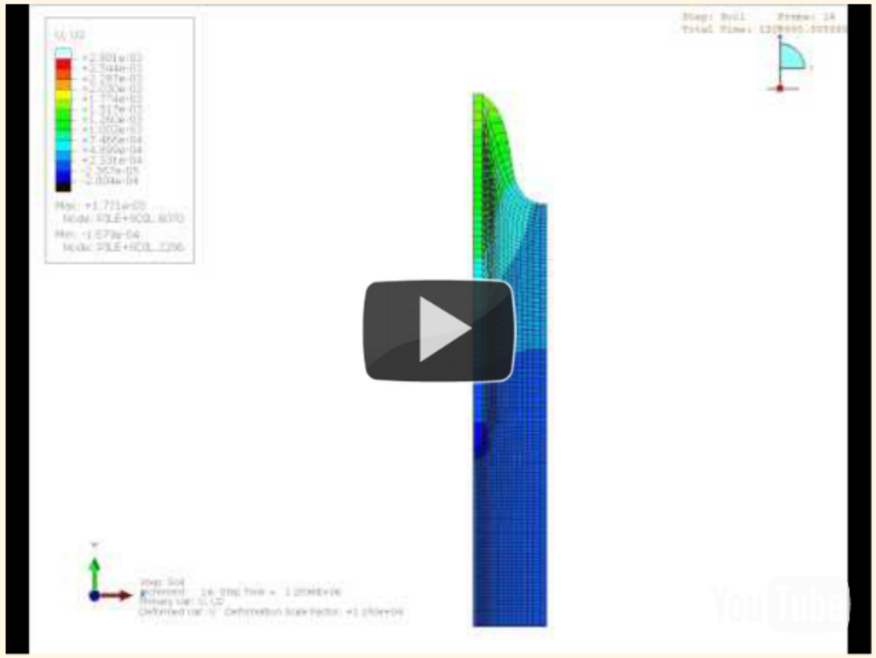

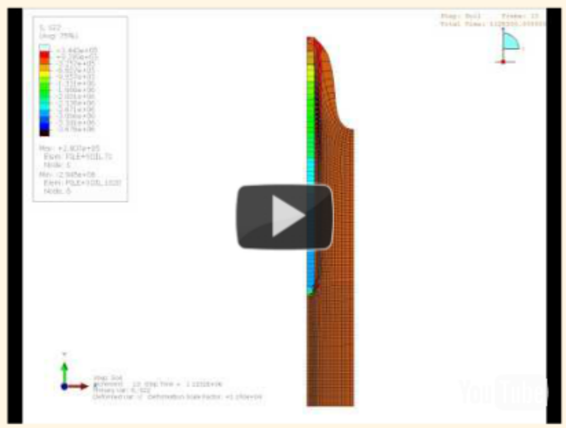

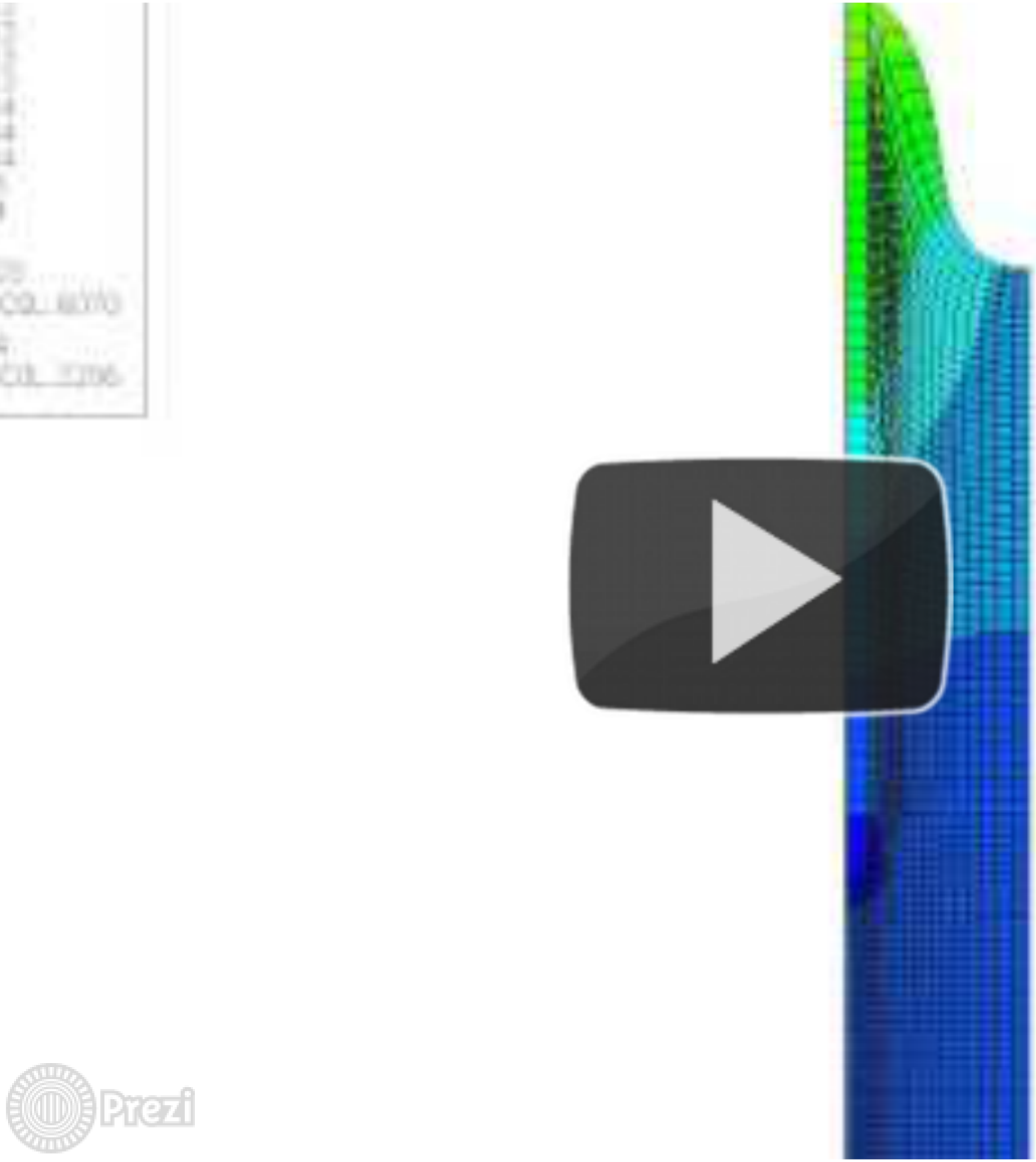

Conclusions

- Environmentally friendly and sustainable alternative energy source.
- Soil properties and soil layering at the site influence stresses, strains and displacement of HEP.
- Max thermal axial strains occurred at the pile head at the end of heating period.
- Heating induced additional compressive stresses in the pile while increasing mobilized shear stresses in the surrounding soils.
- Heating induced negative skin friction in the upper portion of the pile.
- Tensile stresses developed in the pile during cooling phase have been well within accepted limits for the reinforced concrete.

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Thank you!

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